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Test flammability of PVC wall panel with cone calorimetry

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Fire behaviour of PVC wall panel was evaluated by bench scale test with Cone calorimeter. Samples were tested with three incident irradiance heat fluxes to get the minimum heat flux required for ignition of the samples from fitting line. This minimum ignition incident heat flux demonstrates the material is of low fire risk under 20 kW/m², and the panel is safe in small accidental fires. Petrella's arbitrary scale parameters were calculated from the test data and the fire behaviour of the PVC wall panel was classified as intermediate risk. Östman/Tsantaridis' empirical linear regression model and Hansen/Hovde's multiple discriminant function analysis (MDA) were also used in predicting flashover time and classifying the wall panel material from the results of 50 kW/m² tests. The PVC wall panel was classified as FO-categories 1 material which won't reach flashover within test duration of 1200 seconds in ISO9705 room. The results illustrate less relationship between arbitrary scale parameters model and FO-category methods.

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1. Introduction

Polyvinyl chloride, commonly abbreviated PVC, is a general purpose plastic. PVC wall panel is one of the familiar examples used in various decorative applications taking full advantage of its superior printability, adhesion properties and weather ability. PVC has inherently superior fire retarding properties due to its chlorine content, flammability ratings in UL94 is V-0 level, even in the absence of fire retardants. For example, the ignition temperature of PVC is as high as 455 °C, and is a material with less risk for fire incidents since it is not ignited easily [1]. But as other plastics, PVC is still classified as ordinary combustibles [2]. According to the NFPA, the lack of stability of plastics under high temperature conditions and inherent combustibility, have eliminated the use of plastics for applications where a fire resistance rating is a requirement. Thus the fire behavior of PVC products should be classified especially for those close to people's daily lives, such as wall and floor panel used inside rooms. The study of PVC fire behavior could be traced back to early 1980s [3].

To study the fire behavior of material used inside rooms, large scale fire test in ISO 9705 room is a good method to classify the material according to its flashover time, and a classification method is developed based on the ISO room tests, which is called FO-category to predict the flashover time for materials. But the room tests are costly to perform. Bench scale cone test could also be involved in quantifying the degree of fire behaviors [4]. Ignitability, flammability, heat release and smoke emission can be evaluated [5]. Researchers have tried to find rational model to relate cone test data to ISO room classification [6, 7]. Petrella's [8] arbitrary scale parameters are based on 50 kW/m² cone test results and evaluate the fire risk level from peak heat release rate, ignition time and total heat release from the cone tests.

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Kokkala et al. [9] developed classification indexes by applying dimensional analysis and fire growth modeling to the ISO Room Fire Test based on the test results in the Cone Calorimeter at 50 kW/m² irradiance heat flux. This model connects the bench scale test with room scale test. The indexes can be used to group materials based on their predicted time to flashover. Östman and Tsantaridis [10] presented a very simple empirical linear regression model for predicting time to flashover in the room corner test also based on cone calorimeter results from tests at 50 kW/m². Hansen and Hovde [11] evaluated the application of multiple discriminant function analysis (MDA) also on cone test data to predict the FO-category in the room corner test, which made up for the deficiency of Östman/Tsantaridis' model performing poorer for time to flashover above 10 min. We verified Östman/Tsantaridis' and Hansen/Hovde's models on GRP fire behavior by cone and ISO room tests [12] in previous research.

Several other empirical methods were also developed in predicting flashover, such as method of Babrauskas [13], method of McCaffrey, Quintiere and Harkleroad [13], and method of Thomas [13]. The minimum energy release rate of fire required for flashover in a compartment is defined in these methods. It is related to the size and ventilation factor of the compartment, effective heat transfer coefficient, fire spread speed and heat release rate of lining material. Kokkala's and those models which are based on the minimum energy release rate are relatively difficult for use.

Cone tests were carried out to study the fire safety behavior of PVC wall panels, and Petrella's arbitrary scale parameters method, Östman/Tsantaridis' empirical linear regression model and Hansen/Hovde's multiple discriminant function analysis (MDA) were used in evaluation and classification the fire behavior of this material. This will be helpful in fire investigation, material manufacture and utilization.

2. Test procedure and results

The tests were performed with the cone calorimeter in Henan Province Key Laboratory of Coal Mine Methane and Fire Prevention, Henan Polytechnic University. This calorimeter is based on "the oxygen consumption method", and meets all existing standards including ISO5660 and ASTM E1354. Type is Cone Calomrime TER2000.

Nine samples of PVC wall panel materials of average density 1649 kg/m³ (100 mm×100 mm and 1.2 mm thickness) provided commercially by Zibo DaTong Plastic Company were tested in a horizontal orientation under three levels of the incident heat flux 25, 35 and 50 kW/m². The samples were labeled as WP-25A to WP-25C, WP-35A to WP-35C, and WP-50A to WP-50C corresponding to incident heat flux level and test serials.

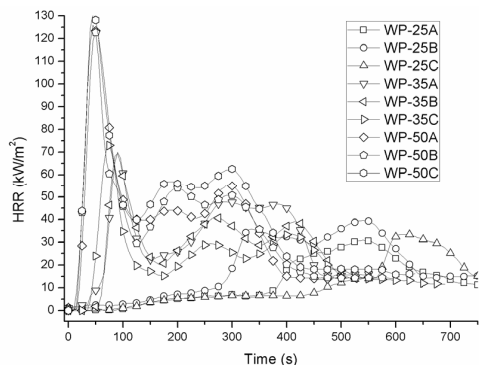


Fig. 1. HRR of Cone Tests.

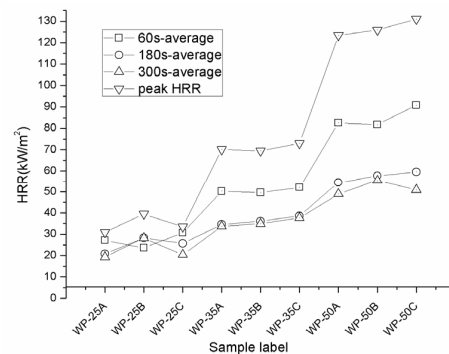


Fig. 2. Average and peak of HRR in cone tests.

The samples were prepared according to cone test requirements. To avoid the edge effect, each sample was positioned on a sample plate with edge and bottom was covered by an aluminum foil. The effective test surface area of each sample was about 0.008836 m². The nominal exhaust system flow rate for all tests was about 0.24 m³/s. Before testing all materials were conditioned under room temperature 23 ± 2 °C and a relative humidity of 50 ± 5% for 1 week.

Figure 1 illustrates the heat release rate curves of the nine tests. All curves exhibit multi-peak shape. For the 50 kW/m² tests and 35 kW/m² tests, the first peak is followed by an evident char procedure which causes the curve to fall down.

Figure 2 gives the three average-HRRs, which is the average HRR within 60, 180, and 300 seconds after ignition. The peak HRR of these each test is also included. The average HRRs of 25 and 35 kW/m² tests are closer together than those of 50 kW/m² tests.

Material ignition properties were derived by the method of Janssens [14] by plotting the irradiance heat flux against the reciprocal ignition time (see Fig. 3). The tests reveal that the minimum heat fluxes required for ignition are about 24.91

kW/m^2 . This heat flux is beyond the so-called the flashover heat flux at floor level of 20 kW/m^2 . It is observed that the material is of low fire risk under 20 kW/m^2 , confirming that PVC sample might be quite safe under small accidental fires.

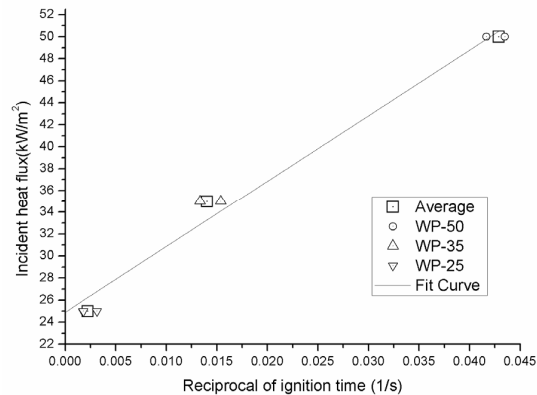


Fig. 3. Effect of incident heat flux on the time to ignition (t_{ig}).

3. Fire Behavior Analysis

3.1. Petrella arbitrary scales evaluation

Two parameters, the flashover propensity x (in $\text{kW/m}^2\text{s}$) and y on THR (in MJ/m^2) were proposed by Petrella [8] for studying the contribution of the materials to flashover and thermal contribution, calculated results are listed in Table 1:

$$x = \frac{\text{peak(HRR)}}{t_{ig}} \quad (1)$$

$$y = \text{THR} = \int_0^{\infty} \text{HRR}(t) dt \quad (2)$$

Arbitrary scales suggested [8] for x are:

- Low risk: 0.1 to 1.0
- Intermediate risk: 1.0 to 10
- High risk: 10 to 100

Similarly, arbitrary scales [8] for y are:

- Very low risk: 0.1 to 1.0
- Low risk: 1.0 to 10
- Intermediate risk: 10 to 100
- High risk: 100 to 1000

Table 1. Calculated results of Eqs. 1 and 2

	WP-50A	WP-50B	WP-50C
x ($\text{kW/m}^2\text{s}$)	5.35	5.21	5.70
x -Risk level	Intermediate risk	Intermediate risk	Intermediate risk
y (MJ/m^2)	18.65	18.98	21.66
y -Risk level	Intermediate risk	Intermediate risk	Intermediate risk

3.2. Östman and Tsantaridis model

Östman and Tsantaridis [10] presented a relatively simple empirical linear regression model for prediction of time to flashover in the room corner test. The model is based on empirical data, and was found to predict time to flashover with good accuracy for several products. Cone calorimeter results from tests at 50 kW/m² are used as input data to this model, which also requires information about mean density of the tested product. The regression model is expressed in the following equation

$$t_{FO} = 0.07 \frac{t_{ig}^{0.25} \rho^{1.7}}{THR_{300}^{1.3}} + 60 \quad (3)$$

where t_{FO} is the time to flashover in the room corner test, t_{ig} is the time to ignition in the cone calorimeter at 50 kW/m², THR_{300} is the total heat release during 300 s after ignition at 50 kW/m² and ρ is the mean density. The model was applied to our set of test data. In the calculations we replaced the observed time to ignition with the apparent time to ignition, as Östman and Tsantaridis [10] did in their calculation, take the ignition time as the definition in Kokkala's model [9]. THR_{300} is then calculated as total heat release during 300 s after apparent time to ignition.

Determining surface material belongs to which FO-categories can help to predict the time to flashover. The FO-categories grouping is based on ISO room tests. The ISO room corner test is used for classification of surface materials. A propane burner placed in a corner exposes the test material to a heat release rate of 100 kW for 10 min and then 300 kW for the next 10 min. The test is terminated if flashover has been reached; otherwise the total testing time is 20 min. A set of separation criteria for grouping products according to the time to flashover (t_{FO}) based on above ISO room test. These criteria divide the tested products into four groups, the so-called FO-categories [11] 1 to 4.

Surface material belongs to which category is determined by application of the following set of rules:

- FO-category 1: products not reaching flashover during 1200 seconds of testing time
- FO-category 2: 600 seconds $\leq t_{FO} < 1200$ seconds
- FO-category 3: 120 seconds $\leq t_{FO} < 600$ seconds
- FO-category 4: $t_{FO} < 120$ seconds

Calculated t_{FO} are all listed in Table 2 for the three samples under 50 kW/m². Two of them are more than 1200 seconds show the material should be classified to FO-category 1, one of them is less than 1200 shows it should be classified to FO-category 2.

Surface material can also be determined to belong to which FO-category based on statistical information from cone calorimeter [11], which is called multivariate statistical method. This method may find links among different variables that are recorded in cone calorimeter tests, such as time to ignition, smoke gas concentrations, heat release rate, specimen mass loss, optical smoke density, density and thickness of samples.

3.3. Hansen and Hovde model

Hansen and Hovde [11] evaluated the application of multiple discriminant function analysis (MDA) to deal with cone calorimeter data, which could be used to predict the FO-category in the room corner test with satisfactory accuracy. MDA is a multivariate statistical method used to classify cases into groups. The groups are determined based on a categorical dependent variable. By using Fisher's linear discriminant function for classification of cases, the result of this analysis is a set of four linear functions, one for each of the four FO-categories. A new case will be assigned to the FO-category for which the classification function obtains the highest value. Three out of about 20 variables, which give information concerning smoke production, production of CO, HRR, time to ignition, time to extinction etc, were found to be able to distinguish between the four FO-categories were. The selected parameters were

- $z_1 = \rho_{\text{mean}}$ (kg/m³) = mean density
- $z_2 = THR_{300}$ (MJ/m²) = total heat release during 300 seconds after apparent time to ignition.
- $z_3 = \ln(FIGRA_{cc})$ where $FIGRA_{cc}$ is the maximum value of the ratio between HRR and time when HRR was measured.

Anne Steen Hansen [11] gave the four classification functions that are expressed as follows:

$$F_{FO1} = 0.01789z_1 - 0.06057z_2 + 0.971z_3 - 7.910 \quad (4)$$

$$F_{FO2} = 0.01492z_1 + 0.03354z_2 + 1.877z_3 - 7.418 \quad (5)$$

$$F_{FO3} = 0.008589z_1 + 0.409z_2 + 2.721z_3 - 13.406 \quad (6)$$

$$F_{FO4} = 0.0000256z_1 + 0.347z_2 + 3.621z_3 - 9.215 \quad (7)$$

$\ln(\text{FIGRA}_{cc})$ is 0.90016, 1.02165, and 1.0685 for test WP-50A, WP-50B, and WP-50C respectively. Substitute these data into Eqs. 4-7, and the results are listed in Table 2.

Table 2. Calculation results of MDA for test WP-50A, WP-50B, and WP-50C

	WP-50A	WP-50B	WP-50C
F_{FO1}	21.5074	21.6314	21.5376
F_{FO2}	19.4296	19.6543	19.8194
F_{FO3}	9.8001	10.0898	11.1579
F_{FO4}	-0.3266	0.0786	1.0464
$t_{FO}(s)$	1280	1303	1093

For the three samples under 50 kW/m² heat flux, all F_{FO1} values give the largest value of all the four Fisher's liner discriminate functions.

Thus, the wall panel material can be determined as a member of FO-category 1, which would not reach flashover in ISO room test within 1200 seconds. The calculated results from Östman/Tsantaridis' empirical linear regression model and Hansen/Hovde's multiple discriminant function analysis (MDA) are the same in predicting flashover time and classifying the wall panel, except for WP-50C, but the t_{FO} of this test is close to 1200 seconds. It is the same as Hansen and Hovde [7-11] mentioned that the model by Östman and Tsantaridis is excellent at predicting time to flashover before 10 min of testing time, *i.e.* predicting membership of FO-categories 3 and 4. This model does not perform so well when no flashover is the correct answer, *i.e.* FO-category 1. The model based on multivariate discriminant analysis has the highest precision of all the models evaluated for FO-categories 1 and 2. These models should be used together in the same procedure to evaluate fire behaviour of materials and verify each other, and that would be helpful to improve the reliability of prediction.

4. Conclusions

Cone calorimeter data can be used to derive useful information on studying of fire behaviour of polymers. Based on these data and rational developed models, prediction of flashover time in the ISO9705 room corner tests leading to fire behaviour classification is feasible.

The results from both the arbitrary scale parameters method and FO-category prediction method illustrate that the PVC wall panel is difficult to ignite under small accidental fires with low heat flux. But the relationship between these two kinds of method seems to be separated. The intermediate fire risk does not correspond to a specific F-category, or *vice-versa*.

Similar results of fire behaviour classification of PVC wall panel can be obtained from Östman/Tsantaridis' empirical linear regression model, Hansen/Hovde's multiple discriminant function analysis (MDA) model. Classification with more than one model could derive more reliable results avoiding overestimate or underestimate the fire safety properties of material.

More room scale experiments are needed to conduct to verify and improve existing models, Round-Robin data exchange among fire research institutes is necessary. Furthermore, thermal analysis methods of mini-scale test of material should be included into the model establishment. Pyrolysis dynamics will help the understanding the fundamental thermal behavior of materials leading to macroscopic fire behavior.

Acknowledgements

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